

Changes in the shoreline at Paradip Port, India in response to climate change

B. Gopikrishna^a, M.C. Deo^{b,*}

^a Central Water and Power Research Station, Pune 411024, India

^b Indian Institute of Technology Bombay, Mumbai 400076, India

ARTICLE INFO

Article history:

Received 30 March 2017

Received in revised form 30 November 2017

Accepted 3 December 2017

Available online 7 December 2017

Keywords:

Shoreline changes

Climate change

Numerical models

Erosion

ABSTRACT

One of the popular methods to predict shoreline shifts into the future involves use of a shoreline evolution model driven by the historical wave climate. It is however understood by now that historical wave conditions might substantially change in future in response to climate change induced by the global warming. The future shoreline changes as well as sediment transport therefore need to be determined with the help of future projections of wave climate. In this work this is done at the port of Paradip situated along the east coast of India. The high resolution wind resulting from a climate modelling experiment called: CORDEX, South Asia, was used to simulate waves over two time-slices of 25 years each in past and future. The wave simulations were carried out with the help of a numerical wave model. Thereafter, rates of longshore sediment transport as well as shoreline shifts were determined over past and future using a numerical shoreline model. It was found that at Paradip Port the net littoral drift per metre width of cross-shore might go up by 37% and so also the net accumulated drift over the entire cross-shore width by 71%. This could be caused by an increase in the mean significant wave height of around 32% and also by changes in the frequency and direction of waves. The intensification of waves in turn might result from an increase in the mean wind speed of around 19%. Similarly, the horizontal extent of the beach accretion and erosion at the port's southern breakwater might go up by 4 m and 8 m, respectively, from the current level in another 25 years. This study should be useful in framing future port management strategies.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

The stability of shorelines is continuously under threat because of changes to the natural environment brought about by the agencies of wind, waves, tides, currents, and also due to human intervention that leads to changes in the dynamic equilibrium prevalent at a given coastal stretch. It is well known that anthropogenic structures change the natural flow of currents and sediments causing alterations in the local sediment budget and hence in the patterns of prevalent accretion or erosion. As a result, shifts in shorelines happen over both short and long terms. The change in the hydrodynamic circulation as a result of constructing breakwaters diverts littoral currents as well as sediment flow such that a slack flow and siltation result up-drift and strong flow and erosion happens down-drift. The dredged navigational channel is further subjected to dumping of sediment material requiring continuous maintenance dredging (Kudale, 2010).

There are various methods to determine such changes in shoreline configurations, and these include collection of (i) hydrodynamic and morphological data as well as beach profiles, (ii) aerial photography,

(iii) Global Positioning System (GPS) based surveys, (iv) Airborne Light Detection and Ranging (LiDAR) based surveys, and (v) historical satellite imageries. Some of more recent methods under the category of remotely sensed techniques include analysis of sophisticated video camera images (Sobral et al., 2013; De Santiago et al., 2013), infrared camera-based imaging (Watanabe and Mori, 2008), unmanned aerial vehicle (UAV) and drone system (Mancini et al., 2013), and synthetic aperture radar along with a combination of sequential images and tidal models (Mason et al., 1995, 1999; Liu et al., 2013). Very recently, the use of marine navigation radar for spatial and temporal imaging of waterline and its coupling with tide elevation records has been presented by Bird et al. (2017). The information so collected can be analyzed using empirical or statistical techniques or more satisfactorily by modelling the physical process of sediment flow into differential equations and solving them using numerical techniques. Various comprehensive software packages that carry out numerical modelling of wave propagation, flow hydrodynamics and sediment transport in an integrated manner are available for use in this regard (Reeve et al., 2015).

An added concern of recent origin to the perpetual problem of shoreline instability is the impact of climate change. Harbours and ports are located in areas vulnerable to climate change impacts. There is an unequivocal evidence presented in recent past to confirm that the climate

* Corresponding author.

E-mail address: mcdeo@civil.iitb.ac.in (M.C. Deo).

is warming (Becker et al., 2011; IPCC, 2013). While the general effects of port structures on surrounding shorelines as well as on neighbouring ports have been studied well so far, including many Indian locations (Mohanty et al., 2012; Mani Murali et al., 2001, 2015), the additional impact of changing climate has received less attention excepting some attempts, for example by Trenhaile (2010) and Zacharioudaki and Reeve (2011).

The shoreline changes are strongly influenced by changes in wave conditions, which are projected to intensify in future at various locations over the world (Young et al., 2011) and also along the coast of India (Bhaskaran et al., 2014). In this light Rajashree et al. (2016) demonstrated how a small stretch of an uninterrupted shoreline at Udupi along the west coast of India can experience enhanced erosion as a result of climate change in future.

The present work analyzes the impact of global warming at the Port of Paradip, which is a major port in India situated along its east coast. The methodology involves considering wind data produced by a regional climate model (RCM) over past as well as future 25 years, simulating waves with this input, and running a numerical shoreline evolution model using such wave information, and further evaluating changes in the shoreline from past to future.

The area where the port of Paradip presently exists was once a mangrove swamp used for hunting fish and collecting wood. In 1948 the then Government of India decided to build a port between the existing ports of Visakhapatnam at South and Calcutta at North. Accordingly in 1966 the 8th major port of India or the port of Paradip was built (Fig. 1). The port is protected by two breakwaters of lengths 1220 m (south breakwater) and 540 m (north breakwater). The approach channel initially had a draft of 12.8 m, length of 2020 m and width of 190 m at the entrance aligned at 120° to North. Later, the channel draft was deepened to 17.0 m and its width was extended to 240 m at the bottom to accommodate large crude carriers. Since 2015, the approach channel is being dredged to increase its depth further to 18.7 m in order to handle the large sized ships. There was some damage to the south breakwater due to a cyclone in October, 1999 and as a counter-measure its length was extended by another 100 m in the direction of the approach channel. In order to prevent the high erosion noticed in 1970's as a result of construction of the breakwaters a seawall of 5 km length was erected at the down-drift side (northward). Currently, another

counter-measure in the form of an offshore breakwater of 1600 m length is planned in near future.

The coastal currents in this region are unidirectional beyond the 5 m depth contour and they change seasonally. The tidal range in the area is 2.25 m during spring tides and 1.10 m during the neap condition. The highest high water level (HHWL) is 3.5 m while the lowest low water level (LLWL) is 0.7 m and the mean sea level (MSL) is 1.65 m. The average wind speed is in the range of 35–42 km/h in summer and 18–24 km/h in winter. This area receives an annual average rainfall of 1480 mm (www.paradipport.gov.in).

Along the east coast of India two other major ports, namely Visakhapatnam and Chennai, are located southward at distances of around 500 km and 1300 km, respectively. A study by Sarma (2015) indicates that at these places the net littoral drift is northerly and has magnitude of 0.55×10^6 and 0.46×10^6 m³, respectively. Another related work by Panigrahi et al. (2010) indicates that the net northerly drift at Visakhapatnam is of the order of 0.40 – 0.60×10^6 m³ and that the resulting sediments deposited at the up-drift side of the two harbor breakwaters are regularly pumped to the down-drift side in order to combat the erosion taking place over there. Authors also report that the average longshore current around this region has strength of around 0.5 m/s and it is mostly generated by the waves whose direction is close to southwest (SW) or northeast (NE) as per the SW or NE monsoon season.

The results of this study in the form of future rates of sediment transport and shoreline change rate may help the port authorities to undertake counter-measures to mitigate their effects such as appropriately budgeting the dredging expenses and adopting soft or hard erosion prevention measures.

2. Materials and methods

2.1. Study area

Paradip port is one of the major ports of India located at latitude $20^\circ 15' 55''$ N and longitude $86^\circ 40' 35''$ E along the east coast of India (Fig. 1). Since the development of the port in 1966, the site is subjected to accretion and erosion on either side of the port where the coastline was earlier stable for a period of preceding 60 years.

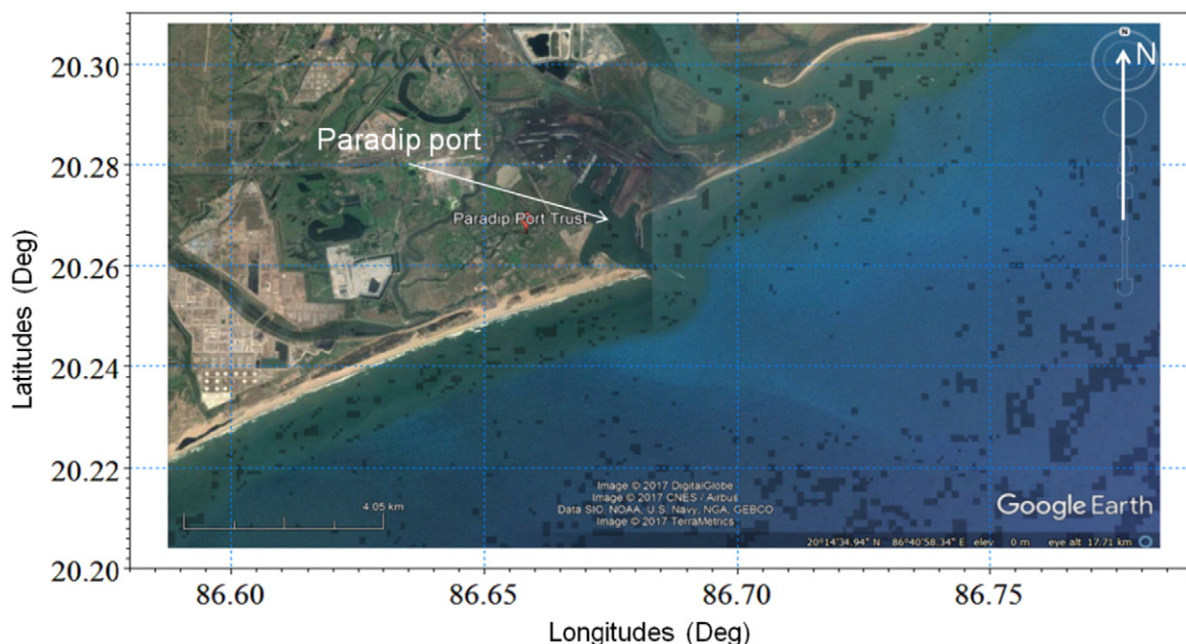


Fig. 1. The study area around Paradip Port (Google image, 15.03.2017).

The site is subjected to both SW and NE monsoons. The waves resulting from the SW monsoon are strong and generally vary in heights from 1.25 m to 3.75 m and in periods ranging from 8 to 17 s (Varadarajulu and Hari Krishna, 1979; Sundar et al., 1987). During the NE monsoon, relatively low wave activity prevails, with heights reaching around 2.25 m with associated periods of 11 s (Varadarajulu and Hari Krishna, 1979). The surface currents induced by wind and tides run parallel to the coast with an average velocity of 0.5 m/s beyond the 5 m depth with main direction varying from SW during December–May to NE during June–October. The current observations by Sanil Kumar et al. (2006) indicated that the typical current in the month of May 2006 was of the order of 0.1–0.8 m/s, while those in the month of November of the same year were higher and around 1.2 m/s.

The site is oriented along the NE direction and the predominant direction of wave approach is from south. The net movement of littoral drift is thus toward north. One of the past studies (Sundar et al., 1987) had indicated that the net littoral drift was along the NE direction and it was of the order of 0.75×10^6 m³ annually, while another work (Sanil Kumar et al., 2006) estimated it to be higher and of the order of about 1.00×10^6 m³. The pattern of deposits of sand spits near river mouths had further confirmed that the direction of the net drift was to the NE.

2.2. Numerical wave and shoreline evolution models

In this study we have used numerical models: Mike-21 spectral wave (SW) and LITPACK developed by DHI, Denmark, for simulation of wind waves and evolution of shorelines, respectively. The model dealing with wave simulations basically solves the energy balance equation using different numerical schemes. It takes into account a large number of physical processes including the wave growth by action of wind, non-linear wave-wave interaction, energy dissipations by white-capping, depth-induced wave breaking and bottom friction, refraction due to depth variation, and wave-current interaction for wave simulations. The evolution of directional wave spectrum with time and space gives the average wave parameters of significant wave height, H_s , average zero-cross wave period, and average wave direction among other products at selected spatial and temporal intervals.

The model determining the sediment transport and shoreline evolution is a comprehensive numerical model integrated with hydrodynamics and non-cohesive sediment transport components. This is done through certain built-in modules which simulate cross-shore distributions of longshore current and longshore sediment transport for both regular and irregular sea states for a given coastal profile. The computation is performed in two parts. First, the hydrodynamic module computes the longshore current considering shallow water wave propagation, wave set-up and breaking and the sediment transport module calculates the sediment transport based on the input from the hydrodynamic conditions.

The evaluation of the non-cohesive sediment transport is done by solving the vertical diffusion equation. For a given cross-shore bed profile and over a given time duration the cross-shore distribution of wave heights, wave set-up, longshore currents and sediment transport is done by solving the longshore and cross-shore momentum balance equation. The evolution of the shoreline is done by considering the effect of sediment sources and sinks as well as diffraction from a structure in the solution of sediment continuity equation. Finally the cross-shore profile changes are determined by solving the bottom sediment continuity equation.

More information of the above numerical models is given in Appendix 1. For further details please refer to DHI (2014, 2016).

2.3. Wind data

The most common way to project future climate is to use general circulation models (GCMs) that operate on global scales. As the GCM

output is available at coarse grids, regional features like land geometry and topography do not get well represented and these calls for their regional down-scaling to carry out location-oriented studies. We thus have several regional climate models (RCMs) as a result. The GCMs or RCMs describe the movement of weather system as per the laws of conservation of mass, momentum, energy, and water in all phases. This also includes heat and moisture balance principles. The resulting differential equations are solved using the numerical methods that carry out space and time discretization over spatial and temporal grids or meshes. Because of insufficient understanding of the underlying physical processes, many sub-processes are approximated through parameterization. The numerical models need input of a variety of geographical and topographical features, covers of sea, vegetation and snow, and sea surface temperature, all over the entire globe. Further, the model outcome is refined at every time step by assimilating data collected through wave rider buoys, satellites, merchant ships and land stations.

These climate models are run for future scenarios of global warming in response to a certain increase in greenhouse gas emissions and account for societal response to reduce such emissions. These scenarios are classified as per likely population growth, economic development, and technological innovations (<https://www.ipcc.ch/ipccreports/tar/wg1/pdf/TAR-13.pdf>). The warming and response scenarios are called Representative Concentration Pathways (RCPs) and these are specified as per their warming potential and societal response encapsulated into a certain index or radiative forcing to run the GCM (Hemer et al., 2007; Taylor et al., 2012). The output variables of temperature, pressure, humidity, wind and precipitation are forecasted at certain intervals of time. It is to be noted that the information on other climate variables, such as waves or currents, is required to be derived from these atmospheric variables.

This study uses wind information from an RCM called Regional Climate Model version 4 (Reg-CM4). This RCM has resulted from the 'Co-ordinated Regional Climate Downscaling Experiment' (CORDEX) targeted for South Asia. (<http://cccr.tropmet.res.in/cordex>). It is a dynamically downscaled version of the parent GCM developed by Geophysical Fluid Dynamics Laboratory (GFDL), USA. In this RCM the spatial resolution of wind is $0.44^\circ \times 0.44^\circ$. We have used the wind data belonging to a moderate RCP, namely RCP 4.5. RCP 4.5 is associated with a radiative forcing on earth of the order of 4.5 W/m^2 , a temperature rise of 2.4°C , the emission level of CO_2 of 650 ppm and a stabilized pathway – all until the end of the present century.

This work involves considering two time-slices: one of 25 years in the past (1981–2005) and another of 25 years in the future (2011–2035), and comparing sediment transport rates as well as shoreline configurations evaluated for these two periods. It may be noted that in climate change studies the classical period for statistically analyzing the averages and trends of climate variables such as temperature, precipitation and wind is considered to be around 30 years (IPCC, 2013). Although as per the typical compilation of the data, the information until 2005 is considered as past and the one after the year 2005 is regarded as future projections; in this work we have regarded data after 2011 as future projections in order to consider longer duration (up to 2035) into the future. It is mentioned that the aim of this study is to compare the future conditions with the past and such comparison would be more meaningful and may truly represent the changing climate if based on wind derived from the same modelling outcome, namely, CORDEX, rather than one reanalysis and another RCM wind.

Any given GCM or RCM data suffers from certain bias arising out of inadequate modelling of the physical process as well as computational approximations and this needs to be removed before their application. This is done by comparing raw data with some more accurate wind data. The latter dataset used herein belonged to Climate Forecast System Reanalysis (CFSR) of National Centre for Environmental Protection and National Centre for Atmospheric Prediction. (<http://cfs.ncep.noaa.gov/cfsr/>). The suitability of CFSR data for carrying out wave simulations was earlier confirmed by Cox and Cardone (2011). Table 1 gives the

Table 1
Spatial domain and resolutions of different types of wind.

Wind data	Spatial Domain	Spatial resolution	Temporal resolution
CORDEX Historical and Future	10S–25N 55E–95E	0.44°	24 h
CFSR	10S–25N 55E–95E	0.50°	6 h

physical domain as well as the spatial and temporal resolutions of the CORDEX and CFSR datasets.

For removing the bias in RCM data we have used the common method of quantile mapping that involves matching the probability distribution of given RCM with that of a standard dataset with respect to various low and high end quantiles (Li Haibin et al., 2010). Although there are alternative parametric and empirical methods to remove the bias, in a

comprehensive work based on global wave data analysis Parker and Hill (2017) did not find much difference across them. In our work the standard or target wind data pertained to the CFSR wind corresponding to the period 1981–2005. It is emphasized that the future wave simulations were also performed using the bias corrected wind, similar to the historical wave simulations.

The basic statistics of mean, maximum and standard deviation of wind speeds pertaining to CFSR, raw CORDEX, “bias-corrected CORDEX” past and “bias-corrected CORDEX” future are given in Fig. 2a. The underlying location was 30 km offshore Paradip Port. Additionally Fig. 2b gives probability density functions (pdfs) of raw CORDEX past wind bias-corrected CORDEX wind while Fig. 2c gives the pdfs of raw projected CORDEX wind and bias-corrected projected CORDEX wind. It may be seen that, as compared with the CFSR wind, the mean of the raw CORDEX wind is low although its unique maximum value is high and the standard deviation is less. After the bias correction, the mean and the standard deviation is raised. A similar impact is seen in case of

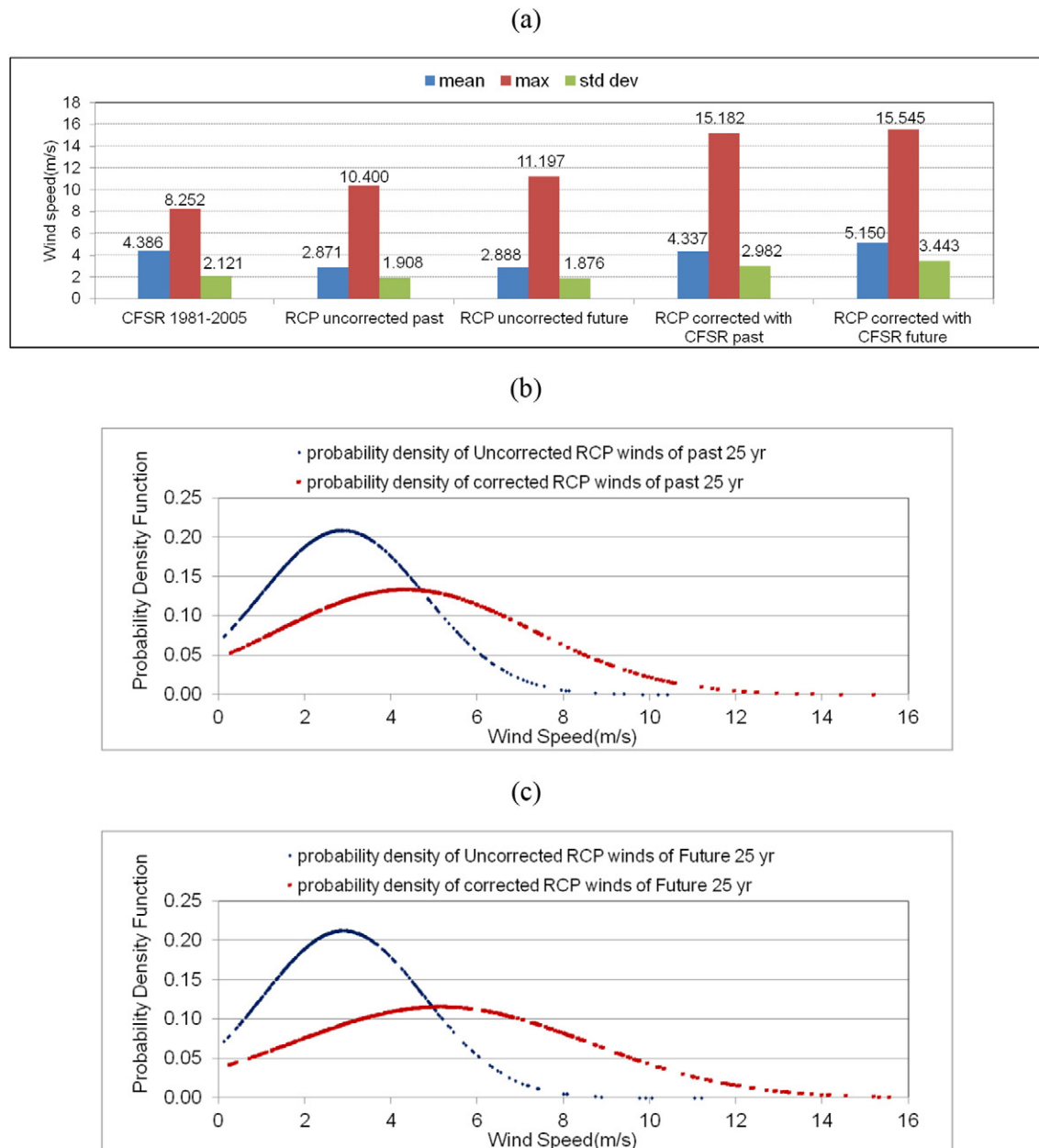


Fig. 2. Comparison of raw and bias-corrected wind at a location 30 km offshore Paradip (a) Basic statistics, (b) probability density functions of past wind, (c) probability density functions of future wind.

projected data. Fig. 2a and b show that the effect of bias removal is increase in the frequency of occurrence of higher waves. It may however be noted that this comparison may not be directly linked to the final outcome of the wave simulation since it is done with respect to a single offshore point, whereas the resulting waves are generated by wind covering a large physical domain as well as by the swells approaching from the vast southern area.

2.4. Bathymetry and other types of data

In order to retrieve the local bathymetry, a global model domain ranging from 10°S to 25°N latitudes and 55°E to 95°E longitudes (Fig. 3) was considered. The scatter contours in the deeper zone belonged to the source of ETOPO1 of National Geophysical Data Centre, Colorado, USA while in shallow water they pertained to that of C-Map of DHI, Denmark. The combination or prioritisation of both these datasets was in the ratio 0.5:0.5 and their triangular interpolation was performed using the natural neighbour method. Fig. 4 shows the nearshore bathymetry at Paradip in Universal Transverse Mercator (UTM) coordinates and drawn at 1 m contour intervals along with the wave data extraction point at 12 m depth referred to later.

The validation of the numerical wave model called for in-situ wave measurements and these belonged to a location: Kovvada situated south of Paradip (Fig. 3). The waves here were earlier measured by Nuclear Power Corporation, India, using an acoustic Doppler current profiler (ADCP) for a period of one year during 2011. The depth of water where the ADCP was deployed was 15 m.

Additionally, an admiralty chart: INT 7418-3310 of the year 2002 drawn in the scales of 1:15,000 and 1:60,000 was considered to know

the shoreline configuration and nearshore bathymetry (Fig. 5a). The cross-shore profile obtained from this chart was at 3.0 km southward from the southern breakwater of the Paradip port. It spanned over a distance of 1.9 km ranging from the berm height of +4 m to the −12 m contour. Fig. 5b–d further show satellite imageries at Paradip in the years 1973, 1990 and 2006 along with the shoreline delineated on the basis of the year 2002 from the admiralty chart and indicate general time-wise changes in shoreline configuration. The global land survey compilations by the United States Geological Survey and National Oceanic and Atmospheric Administration, USA in three different years, namely, 1973, 1990 and 2006, and in different spectral bands were used. The resolution of imageries varied from 15 m to 60 m.

This study additionally involved the use of ship-reported wave data gathered for 19 years ranging from 1968 to 1986 at Paradip port. This was in the form of wave height distributions along various directions. These data were mainly used to calculate the littoral drift, additionally to that derived from the numerically simulated waves.

2.5. Set-up and validation of the wave model

For effective implementation of the numerical wave model the choice of an appropriate mesh is essential. We adopted an unstructured flexible-size computational mesh consisting of linear triangular elements and facilitating cell-centered finite volume solutions for the entire area. This had coarser resolution of 0.5° in deep sea and finer one of 0.1° near the coastal areas. Such mesh resolution was adopted after several experiments with different mesh sizes that satisfy the computing stability criteria according to which the magnitude of the Courant number should be less than 1.0. The south boundary was assumed to

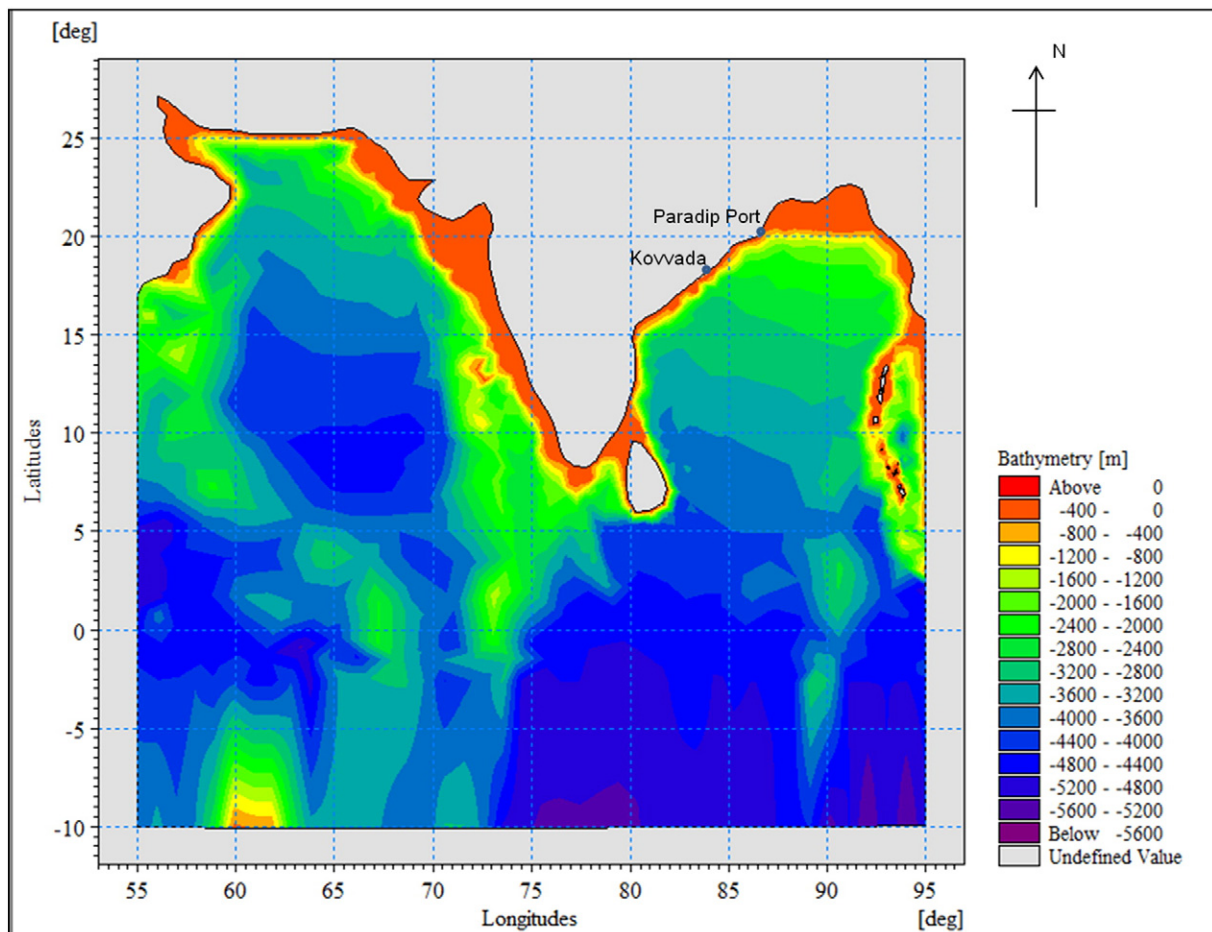


Fig. 3. The wave model domain and the bathymetry.

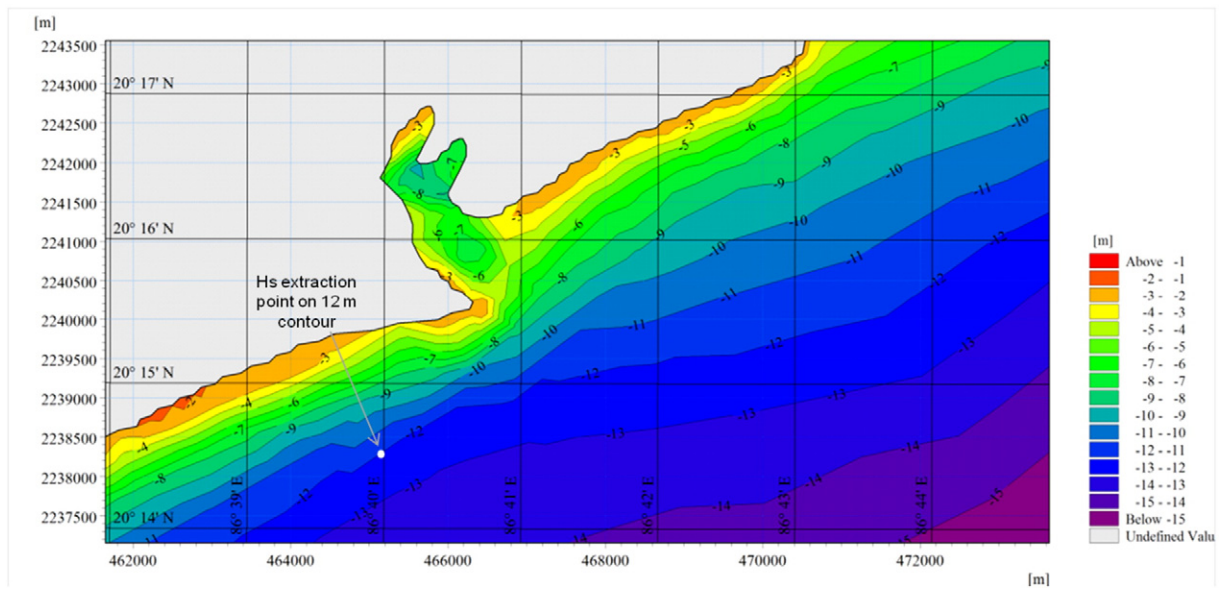


Fig. 4. Nearshore bathymetry of Paradip area in UTM coordinates at 1 m contour interval (CMap module of DHI, 2014) along with the wave extraction point.

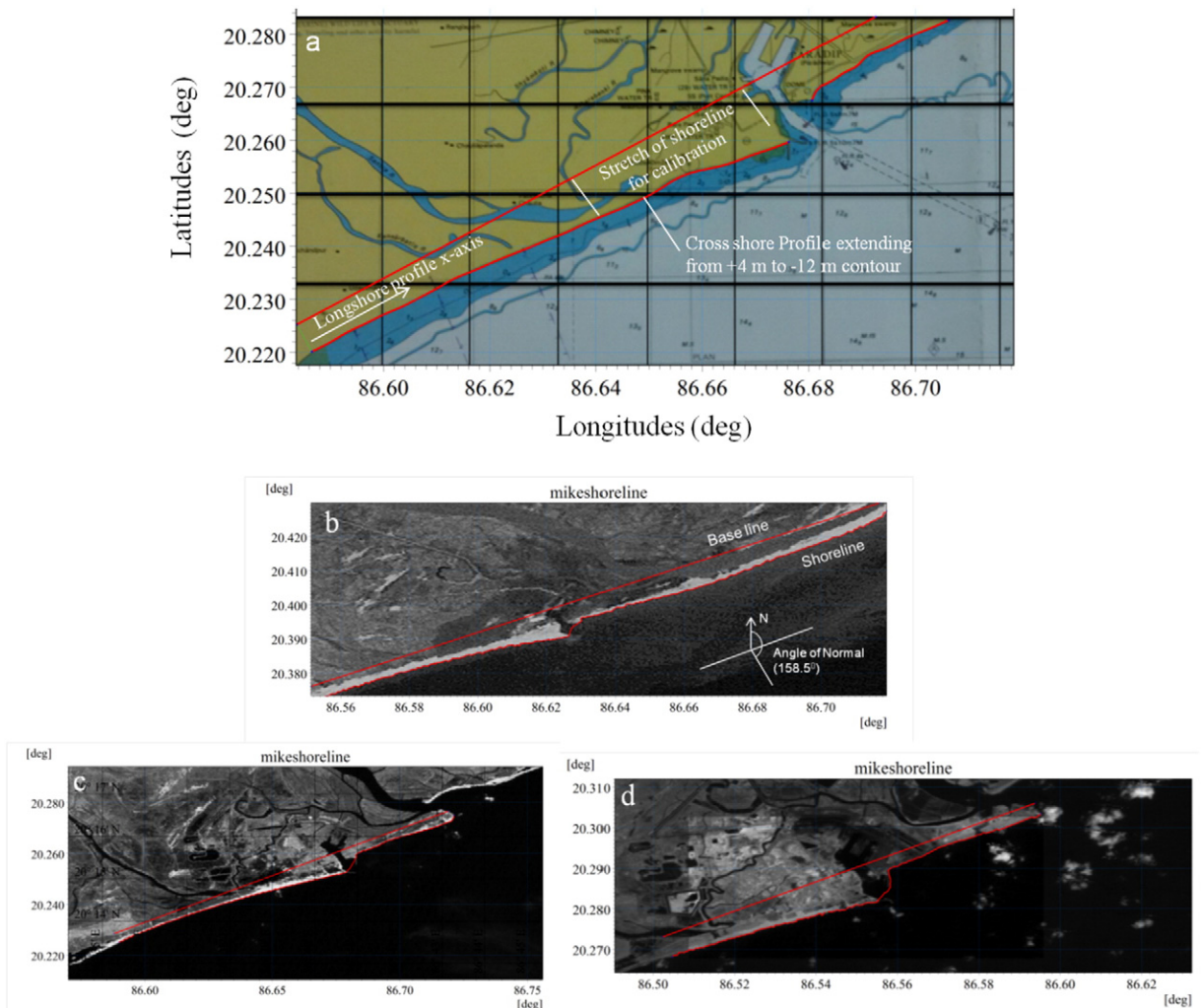


Fig. 5. (a) The admiralty chart for Paradip Port indicating shoreline model features, (b) satellite imagery of 1973, (c) satellite imagery of 1990, (d) satellite imagery of 2006.

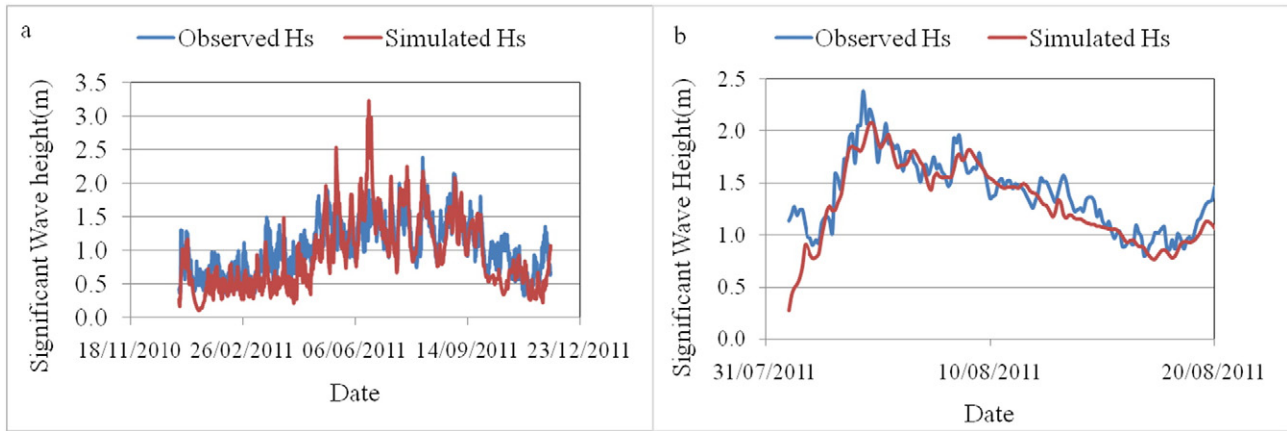


Fig. 6. Observed versus simulated significant wave heights over (a) an entire year, (b) the south-west monsoon season.

be closed and all other boundaries as absorbing ones in the model. The model parameters of white-capping, depth-induced wave breaking and bottom friction control the propagation of waves in response to wind forcing. White-capping quantitatively accounts for wave breaking and it is directly proportional to the rate of energy dissipation (Hanson and Phillips, 1999). Its extent is proportional to the 3rd power of air friction velocity and 3.75th power of the wind speed at 10 m from the sea level (Zhao and Toba, 2001). The bottom roughness is not effective in deep water but becomes influential as the waves approach the shore. A variable time-step interval ranging from 1 to 30 s was used and its value ensured that the stability number was less than unity in all computational nodes.

The output of the numerical wave model in terms of H_s was compared with corresponding wave measurements mentioned earlier and based on ADCP in the year 2011. Fig. 6a shows such comparison over the entire year while Fig. 6b shows the same over some days in the monsoon month of August. The general closeness of the simulations with the observations in both cases can be noticed. In addition to the above qualitative comparison error statistics were also worked out. This showed that for August the root mean square error (RMSE) between the modelled and the target values was 0.35 m, the mean absolute error (MAE) was 0.37 m and the coefficient of correlation (R) was 0.85, indicating closeness of both datasets. As regards the annual evaluation, the RMSE and MAE were higher at 0.540 m and 0.544 m and the R value was also lower at 0.80. The high level of errors at the annual level could have been caused by highly varying seasonal effects. It was noticed that the wave simulation in the fair weather season, typically October–May, was not as good as the monsoon season. This could be because of the multi-modal nature of wave spectra that is difficult to

account for accurately in the modelling, which in turn arises due to the combination of local waves and distant swells coming from the Southern Ocean, as observed by past investigators (Semedo et al., 2011; Glejin et al., 2013; Shanas and Sanil Kumar, 2014). A high amount of seasonality effects in the wave occurrences in the Bay of Bengal have been earlier observed by Patra and Bhaskaran (2016).

2.6. Set-up and validation of the shoreline evolution model

After setting up the wave model the next step was to delineate shorelines from the geo-referenced imageries. A 11 km-long stretch of the coastline oriented approximately along the NE direction was considered. While shorelines can be delineated with the help of certain software tools such as Digital Shoreline Analysis System under the ArcGIS environment, herein we have used an alternative and simpler approach that can be used without the aid of such tools and within the umbrella of the Mike21 software itself. Toward this a method was devised based on finding an appropriate orthogonal from the baseline to the shoreline at several points or vertices. This involved following procedure (Fig. 7): (i) draw a baseline roughly parallel to the shoreline orientation; (ii) divide the baseline and shoreline into number of segments, each bound by vertices on either side; (iii) calculate the slope of the baseline (m_1) (note that the slope of the line perpendicular to it (m_2) must satisfy the condition: $m_1 \cdot m_2 = -1$); (iv) from the given vertex point along the baseline, draw several connecting lines to the vertices of the shoreline and find the slope of each; and (v) select that orthogonal whose slope satisfies the condition: $m_1 \cdot m_2 = -1$. This is the exact perpendicular transect and its length can be determined by any distance formula. In that way the distance between the baseline and the shoreline point

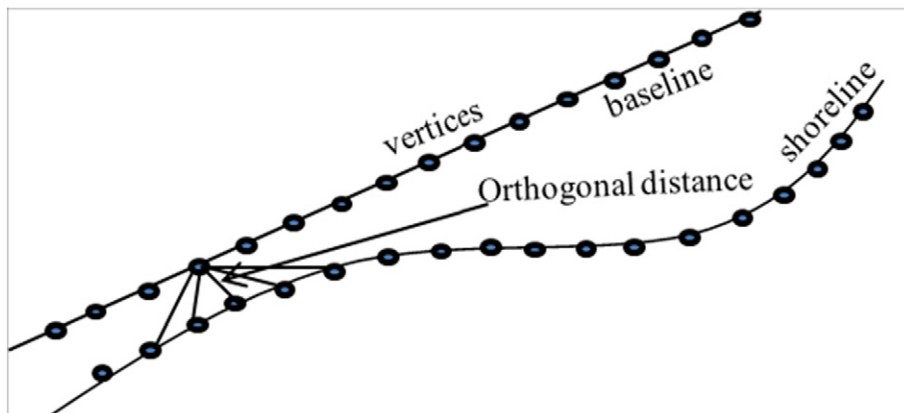


Fig. 7. Delineation of shoreline from the baseline.

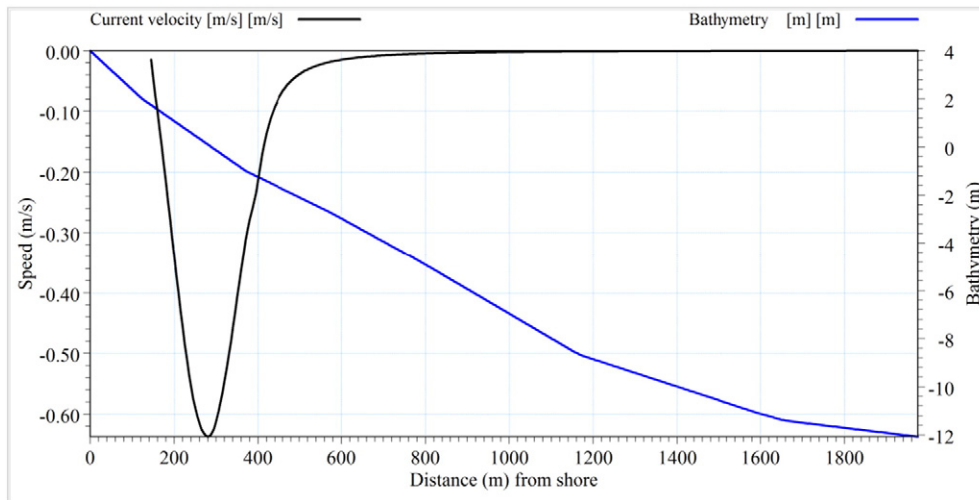


Fig. 8. The longshore current and cross-shore profile along the offshore direction.

can be found out and further used to carry out the linear regression aimed at knowing the shoreline change rate.

The shorelines were delineated for the years 1973, 1990 and 2006 with the above procedure. The cross-shore depths were extended up to the 12 m contour known from the admiralty chart of the study area and interpolated to 5 m sized grids in the model. The sediment gradation sample obtained from the Paradip Port authority was used to know the mean sediment diameter, D_{50} .

The shoreline model was calibrated against known shoreline configurations and currents. The littoral current, caused by a change in the shear radiation stresses across the shore, is derived from the root mean square wave height and as per the mean water level. Fig. 8 shows how the longshore current, so derived, varying offshore along with corresponding bathymetry. Such model-derived currents were generally found to be comparable with earlier measured currents reported in Sanil Kumar et al. (2006).

The littoral current and drift computations were made, seasonally and annually, on the basis of corresponding seasonal and annual wave climates. This involved the use of roughness and fall velocities of sediments determined during the calibration of the shoreline model. The bed roughness and depth of closure played a crucial role in calibrating the shoreline model. The bed roughness varies seasonally, especially in the monsoon season (Omid et al., 2010), and hence the roughness was accordingly adjusted using the relationships established by Wilson (1989) considering the Shield's parameter and Madsen's findings for different grain sizes as mentioned by Camenen et al. (2009) in his paper.

The longshore profile of 1973 was used as the initial shoreline and subsequently the shoreline was simulated for 17 years using ship-reported wave data. It was later validated with respect to imagery of the year 1990, as shown in Fig. 9. Another validation was done with respect to the imagery of year 2009 (Fig. 10) after making the shoreline simulations from 1990 to 2006 based on the annual average wave climate forced by the CORDEX wind data.

3. Results and discussion

3.1. Wave simulations

A comparison of wind speeds extracted at 30 km offshore Paradip for the entire past duration with the same for the entire future duration indicated that in future the mean speed increases from 4.34 m/s to 5.15 m/s, i.e., by 19% with somewhat small increase in the maximum wind speed.

The wave and shoreline models were run for the two time-slices of 25 years each belonging to historical as well as future periods of time. The historical wind was used to generate historical wave data while the projected wind was employed to simulate the future waves. The input wind had a temporal resolution of 6 h and spatial one of 0.25° . The resolution in the geographical space was guided by the computational stability condition that the value of Courant stability number should be less than unity, and this was 0.8 in our case. A changing time-step was used such that such stability was maintained at all computational nodes. The wave data were extracted at an offshore point of

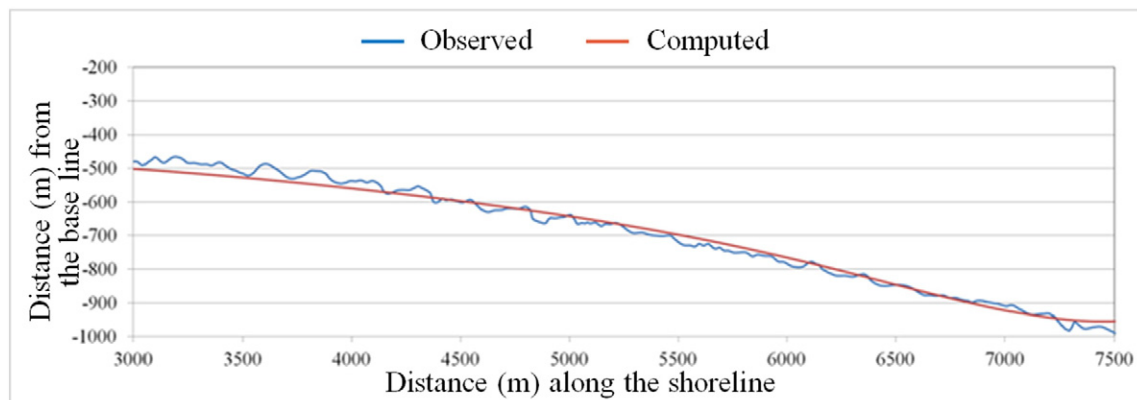


Fig. 9. Validation of the shoreline simulated using ship data with the Landsat imagery of 1990.

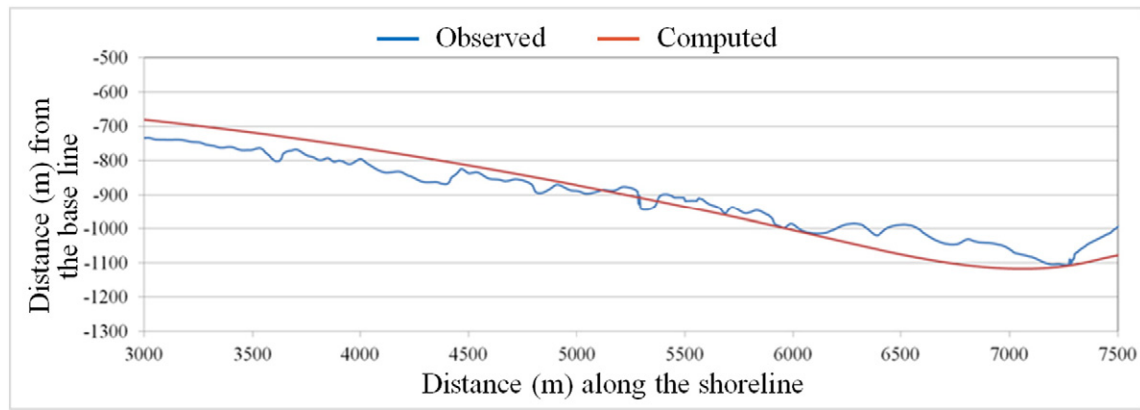


Fig. 10. Validation of the shoreline simulated using past CORDEX data with the Landsat imagery of 2006.

12 m contour and from their nearshore wave transformation was affected up to the shore.

The calibrated wave model was forced with the CORDEX wind of past and future time-slices. At a typical location, which is the offshore point at the 12 m contour from where the wave data were extracted for nearshore wave propagation to the Paradip Port area, the wave rose diagrams were constructed considering the entire past data as well as entire projected data, separately. Fig. 11 shows these wave roses along with the wave rose prepared on the basis of the ship-reported data of 19 years. The comparison of historical ship observations with the waves of the past CORDEX wind shows that in case of the ship data the wave heights were somewhat larger, and directions of wave approach were mostly confined to the sector of south-west (SW) to south-east (SE) as against the CORDEX based past waves. If both past and projected CORDEX based waves are viewed together, we find that generally the wave activity would be stronger in the future, and more so along the SW direction, although frequency of wave approach from the southern side would also increase. The differences across the historical ship observations and the numerical wave data could be attributed to the fact that the latter belonged to a particular location while the ship data pertained to a wider geographical area around Paradip and also to the different data collection and evaluation techniques.

It was seen that while moving from the past to the future 25 years the mean of H_s increased from 0.66 m to 0.87 m, i.e. by 32%. The maximum H_s also rose from 3.42 m to 3.92 m, i.e. by 14%. This was associated with a rise in the standard deviation from 0.48 m to 0.63 m, i.e. by 31%, indicating more turbulence around the mean.

For the same offshore point as above a comparison of the probability density functions of H_s data belonging to past and future time-slices was made (Fig. 12) and this showed that the higher waves

would occur more frequently, and lower waves less frequently, in future, indicating again the intensified wave activity at Paradip Port in the next 25 years. It may be agreed that in this work a collective view of analysis of trends, pdfs, wave roses point to the high rise in H_s in future.

3.2. Littoral drift and shoreline changes

Based on the calibrated models of littoral drift and shoreline evolution, future drifts and shoreline changes were determined. The littoral drift was derived on the basis of annual average wave climates derived from 3 different data sources, namely, ship-reported wave data of 19 years (1968–1986), CORDEX wind data of past 25 years and CORDEX wind data of future 25 years. This is given in Table 2 in terms of annual drifts per m cross-shore (negative or northerly, and, positive or southerly), annual net as well as gross drifts per metre cross-shore, and corresponding accumulated drifts over the entire cross-shore. It may be seen that the drift calculated from the ship-reported as well as the numerically simulated wave data were in fair agreement with each other. Table 2 indicated that the annual net drift at Paradip Port would increase by 37% while the gross one would go up by 24% in the next 25 years as per the CORDEX winds.

Past researchers have analyzed the trends in waves and wind in Arabian Sea, Bay of Bengal and also in the northern Indian Ocean (Hemer et al., 2010; Dobrynin et al., 2012) using historical satellite measurements (Bhaskaran et al., 2014; Hithin et al., 2015; Patra and Bhaskaran, 2016) or reanalysis wind and waves (Shanas and Kumar, 2014; Wu et al., 2017). They generally point to an increasing trend in the annual mean of H_s (Hemer et al., 2010; Shanas and Sanil Kumar, 2014). Dobrynin et al. (2012), based on certain latest RCMs, found that in future both wind and waves would increase in Southern Ocean

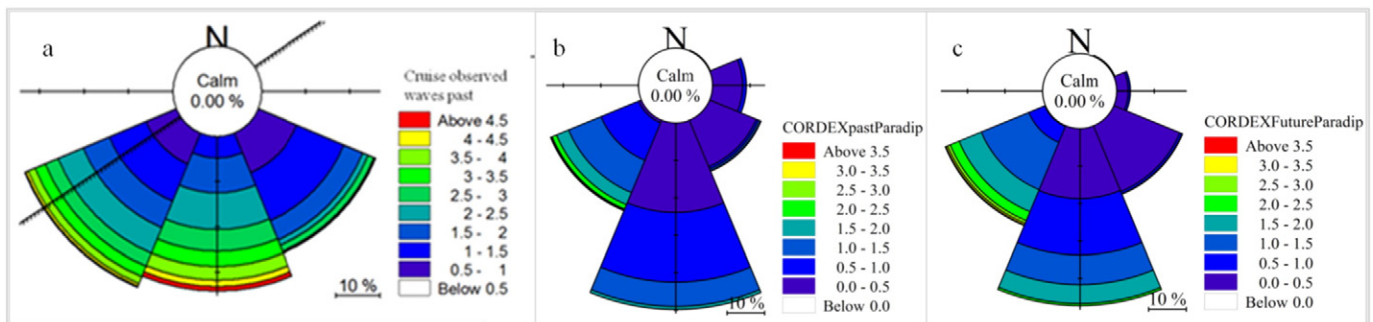


Fig. 11. Wave rose plots derived from (a) ship observed, (b) past CORDEX wind, and (c) future CORDEX wind.

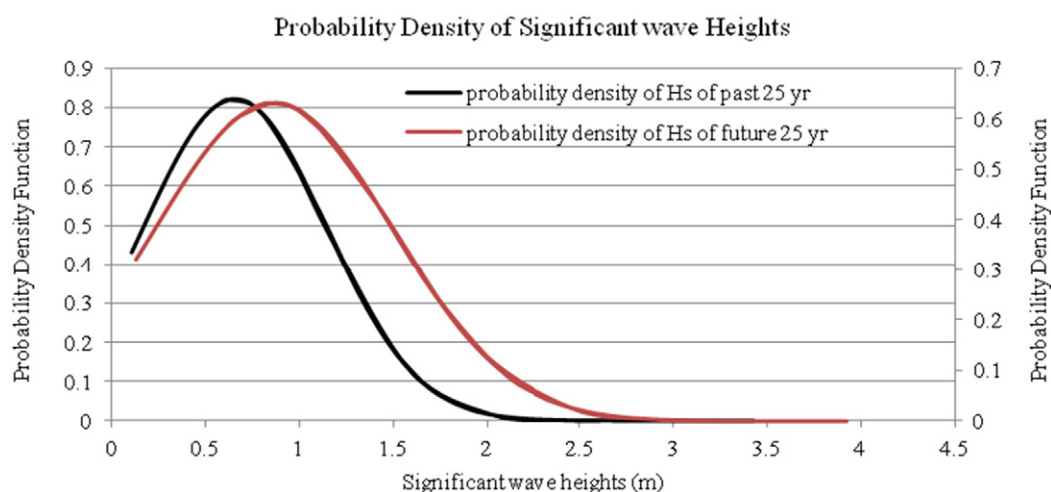


Fig. 12. Probability Density Functions of H_s of past and future time slices.

and this would send swells northwards. Further, as per [Patra and Bhaskaran \(2016\)](#), in the northern Bay of Bengal, higher waves had occurred more frequently in the decade of 2002–2012 than in the immediately past decade. It is worth noting that the changes in waves and wind may not happen in same proportions.

It is felt that the intensification of wave activity reported herein could be due to a rise in the wind speed and its circulation. [Kulkarni et al. \(2016\)](#) analyzed the wind of 10 different GCMs from the CORDEX experiment, offshore India. This was done over two time-slices in the past and future. This study showed that high winds might occur more frequently in future but with somewhat complex change in wind directions.

The observed rise in wave heights in this study compares well with general global trends as say in [Grabemann and Weisse \(2008\)](#), although a local trend in H_s can be different than the global one ([Mori et al., 2013; Dobrynin et al., 2015; Bennet et al., 2016; Wu et al., 2017](#)) since at local level waves may build up as a result of likely changes in local topography, fetch and durations, as well as in wave directions and frequencies of occurrence. As per [Dobrynin et al. \(2012\)](#), in future both wind and waves are projected to increase in Southern Ocean, sending more swells northwards to Arabian Sea and Bay of Bengal, and this may cause a rise in overall wave activity at Indian coasts.

The annual littoral drift accumulation over the entire cross-shore ([Table 2](#)) was $1.05 \times 10^6 \text{ m}^3$ and $1.80 \times 10^6 \text{ m}^3$ for the past and future periods, respectively, showing an increase of 71%. It was noticed that in order to accommodate this increased littoral transport the depth of closure ([Nicholls et al., 1998](#)) would shift horizontally by a distance of 175 m seawards. Such horizontal shift in the depth of closure may call for extending the length of the breakwater in future. The increase in drift can be attributed to the same in causal wave and wind conditions as mentioned earlier in this section.

The above results thus show that at Paradip Port one can expect an increase of 19% in the mean wind speed, 32% in the mean H_s as well as 37% and 24% in net and gross littoral drift rates, respectively, in the future 25 years compared with the past 25 years' conditions. It may be worth mentioning here that a previous study ([DHI, 2016](#)) in South African Waters had pointed out 40–100% increase in the general sediment transport rate caused by 10% rise in mean wind and 26% increase in the wave heights.

The initial shoreline of 1973 considered in this work was associated with two breakwaters at north and south sides of the port, as well as a revetment along the north side of the northern break water ([Fig. 13](#)). The shoreline model was first calibrated and validated for the year 1990 on the basis of annual average waves recorded by merchant ships. It was further run for periods of past and future 25 years each using the CORDEX RCM data. [Fig. 13](#) shows typical results of simulating shorelines of 1990, 2000, 2010 and 2015 on the basis of annual wave climate of the past (based on CORDEX RCM). Note that the left part of [Fig.](#) corresponds to the south side while its right one pertains to the north side of the coastal stretch. It may be seen that the northern side of the north breakwater does not show any erosion/accretion due to the presence of a shore-parallel revetment wall, but the southern side of the south breakwater indicates combination of erosion and accretion over time. The shoreline erosion was highest at the southern breakwater because of the predominant waves coming from south and SW. However at 1.0 to 2.5 km southwards there was marginal accretion over the time. Such accretion was 32 m at the southern 2.5 km distance. The maximum erosion at the southern breakwater was noted as 180 m. A similar plot of shoreline changes was drawn for the future period of 2011–2035 (not shown due to little perceptible difference from [Fig. 13](#) belonging to the past duration) and this showed that from the past 25 years to the future 25 years projection the maximum accretion

Table 2
Littoral drift from different wave data.

Data	– ve drift (m^3/m)	+ ve drift (m^3/m)	Annual Net drift (m^3/m)	Annual Gross drift (m^3/m)	Annual Accumulated Net Drift (Mm^3)	Annual Accumulated Gross drift (Mm^3)
Annual averaged ship wave climate	– 6200	1600	– 4600	7800	1.00	1.30
Annual averaged CORDEX wind simulated wave climate of past	– 5800	1200	– 4600	7000	1.05	1.25
Annual averaged CORDEX wind simulated wave climate of Future	– 7500	1200	– 6300	8700	1.80	2.00

The values of drifts are per m cross-shore.

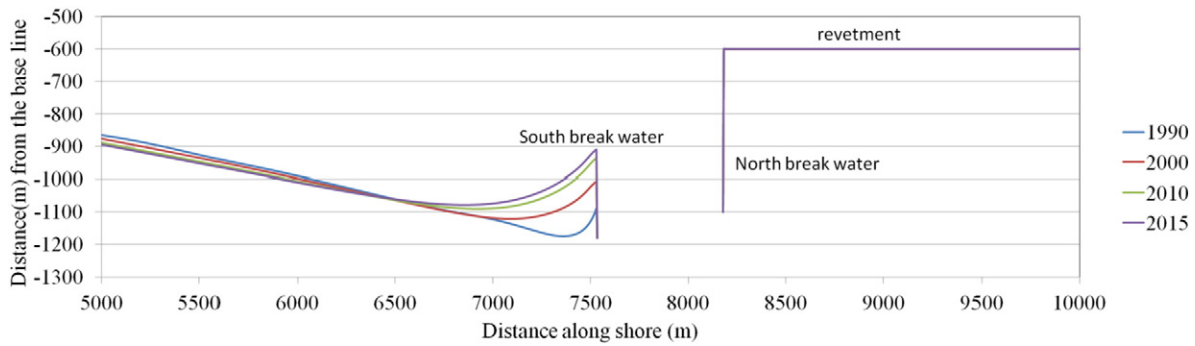


Fig. 13. Simulation of past shorelines based on CORDEX wind.

would increase from 32 m to 36 m and that the maximum erosion from 180 to 188 m.

The study reported above assumes that the cross-shore profiles would not undergo much change in the near future and that no significant human interventions would be made in this coastline in the future time slice. Similarly, we have neglected the effect of the sea-level rise due to global warming in next 25 years. It is reported that the rise in sea level at Haldia, northward of Paradip could be 225 mm in 100 years, as per an analysis of 39 years' tide data by Kundu et al. (2014). Further, based on 150 years tide of gauge data Naren and Maity (2016) predict such a rise to be of the order of 300 mm in next 100 years. This indicates that the sea-level rise at Paradip in next 25 years is expected to be very small and, at the most, less than 75 mm. In this study we have considered only one, although state of the art, RCM in generating future wave data. In future this work needs to be repeated with more advanced climate models when they become available.

This study does not explicitly account for effect of cyclones. The impact of extreme events such as cyclones on a shoreline generally takes place for a short term and it is reversible, as pointed out typically by Paine and Morton (1989), Zhang et al. (2002), Yates et al. (2011) and Davidson et al. (2013), and hence might not be significant in this study. To elaborate, Paine and Morton (1989) analyzed aerial photographs collected during 1974–1982 and found that in spite of occurrence of the Hurricane Allen in 1980 the shoreline along the Texas Gulf coast was restored. Zhang et al. (2002) indicated that even most severe storms had little impact on the shorelines of US East Barrier coasts in the long term. As per Yates et al. (2011), retreating shorelines during storms recover during the low energy periods and this was supported by Davidson et al. (2013) who expressed that the effects of storms dominate only for short term scales, typically less than a decade.

4. Conclusions

This paper presents an attempt to understand future changes in the shoreline configuration at one of India's major ports, Paradip, considering the impact of global warming. Comparisons were made across conditions belonging to two time slices of 25 years each in the past and future. It was found that, compared to the past; the mean wind speed would be 19% higher, changing from 4.34 m/s to 5.15 m/s, although the maximum wind would not undergo much increase. Such a rise in wind would be accompanied by stronger waves at Paradip such that the mean of significant wave heights would increase by 32% and maximum wave heights by 14%. This would be associated with a rise in turbulence around the mean. The higher waves are projected to occur more frequently and lower waves less frequently in future.

The stronger waves as above could increase the littoral drift in the area such that the net drift may go up by 37% and the gross drift by 24% in future 25 years compared with the past 25 years' period. The annual net and gross volumes of sediment transport may increase from 4600 m³/m to 6300 m³/m and 7000 m³/m to 8700 m³/m, respectively

per m cross-shore from the past to the future. The annual littoral drift accumulation over the entire cross-shore might increase by 71%. In order to accommodate this increased littoral transport the depth of closure would shift horizontally by a distance of 175 m seawards. Such a horizontal shift in the depth of closure may call for extending the length of the existing breakwater. The maximum erosion at the southern breakwater was of the order of 180 m in the past 25 years and this could go up by 188 m in the future 25 years.

Acknowledgement

The first author gratefully thanks Central Water & Power Research Station (CWPRS), Pune, India for granting permission to carry out this work and use the available resources for this purpose.

Appendix 1

The numerical models

The third generation spectral wave model (SW) of Mike21 developed by Danish Hydraulics Institute (DHI, 2014), Denmark, used in this work, solves the basic governing equation or the wave action balancing equation written below:

$$\frac{\partial N}{\partial t} + \nabla \cdot (vN) = \frac{S}{\sigma} \quad (1)$$

In the above equation, N or $N(\sigma, \theta)$ = the wave action density spectrum related to wave energy density spectrum E or $E(\sigma, \theta)$ by:

$$N = \frac{E}{\sigma} \quad (2)$$

where σ is the relative angular frequency = $2\pi f$; f = wave frequency in Hz and θ is the direction of wave propagation. Further, ∇ = spatial operator; v = propagation velocity and S = energy source function; t = time.

The Eq. (1) is solved using an implicit finite difference scheme with appropriate boundary conditions. In this scheme the discretization in geographical and spectral space is performed using a cell-centered finite volume method while the time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for propagation of wave action. The solution of the basic governing equation incorporates important wave transformation processes of shoaling, refraction, diffraction, non-linear wave-wave interaction, dissipation of wave energy. For more details of the physical process modelling, please refer to DHI (2014).

The littoral current was computed based on the following equation:

$$-\frac{1}{\rho} \frac{\partial S_{xy}}{\partial x} + \frac{1}{\rho} \tau_w \sin \theta + gDI = \frac{V^2}{C^2} - \frac{\partial}{\partial x} \left(E_c D \frac{\partial v}{\partial x} \right) \quad (3)$$

where ρ is the density of sea water D is the water depth, V is the mean

velocity over depth, c is the resistance factor, S_{xy} is the shear stress due to radiation, τ_w is the wind stress, I is the longshore slope of water surface, θ is the angle between wind direction and coast normal, E_c momentum exchange efficiency, g is acceleration due to gravity and x is the longitudinal coordinate along the coast line.

The radiation stresses play an important role in deciding changes in the mean surface elevation and longshore current as well as in wave current interaction. The model accounts for the variation of S_{xy} due to the directional spreading of waves and also for its reduction in the form of a reduction factor whose value is in between 0.3 and 0.8 (DHI, 2016). The value of 0.3 is for those seas whose directional spread of waves is complex and 0.8 for less spreading cases. In our study we have used the default value of 0.5 during model calibration.

It is to be noted that the above model has limitations in that the cross-shore profile adopted would remain unchanged during the entire simulation period and it cannot account for structure inclination with respect to the coast and rather considers the structure to be perpendicular to the coast.

In order to evaluate the littoral sediment transport as well as to determine the shoreline configurations into future we have used the various modules of the LITPACK software package (DHI, 2016). These modules work on the basis of one-dimensional equation and accordingly formulate and solve the governing equations of conservation of sand volume, applied to an equilibrium profile extending from the coast to the depth of closure. According to the mass conservation principle, in a given space element, the change in the volume of the sediment equals the difference of the volume entering into it and leaving it over a time interval of δt . The governing sand conservation equation is given by:

$$\frac{\partial y_c(x)}{\partial t} = \frac{1}{h_{act}(x)} \frac{\partial Q(x)}{\partial x} + \frac{Q_{sou}(x)}{h_{act}(x) \Delta x} \quad (4)$$

In this equation, $y_c(x)$ = distance from the baseline to the coastline; t = time; $h_{act}(x)$ = height of active cross-shore profile; $Q(x)$ = longshore transport of sediment expressed in volumes; x = longshore position; Δx = Longshore discretization step; $Q_{sou}(x)$ = source / sink term expressed in volume. The user has to specify the value of Δx , while the internal time step Δt of computations is determined from the stability criterion. From an initial coastline position $y_{int}(x)$ the evolution in time is determined by solving the above equation using an implicit finite difference Crank-Nicolson scheme. The shoreline evolution model involves the detailing of bathymetry, hydrodynamic characteristics, and the past shoreline position. The next step involves the transformation of waves from offshore to the nearshore and computations of littoral drift.

References

- Becker, A., Inoue, S., Fischer, M., Eschweiler, B., 2011. Climate change impacts on international seaports: knowledge, perceptions and planning efforts among port administrators. *Climate Change* <https://doi.org/10.1007/s10584-011-0043-7>.
- Bennet, W.G., Karunarathna, H., Mori, N., Reeve, D.E., 2016. Climate change impacts on future wave climate around the UK. *J. Mar. Sci. Eng.* 4:78. <https://doi.org/10.3390/jmse4040078>.
- Bhaskaran, P.K., Gupta, N., Dash, M.K., 2014. Wind-wave climate projections for the Indian Ocean from satellite observations. *J. Mar. Sci.* (S11):005 <https://doi.org/10.4172/2155-9910.S11-005>.
- Bird, C.O., Bel, P.S., Plater, A.J., 2017. Application of marine radar to monitoring seasonal and event-based changes in intertidal morphology. *Geomorphology* 285 (2017), 1–15.
- Camenen, B., Larson, M., Bayram, A., 2009. Equivalent roughness height for plane bed under oscillatory flow. *Estuar. Coast. Shelf Sci.* 81 (3), 1–31.
- Cox, A.T., Cardone, V.J., 2011. On the Use of the Climate Forecast System Reanalysis Wind Forcing in Ocean Response Modelling. 12th International Workshop on Wave Hindcasting and Forecasting and 3rd Coastal Hazards Symposium, Kohala Coast, Hawaii October 31 to November 4 pp. 1–20.
- Davidson, M.A., Splinter, K.D., Turner, I.L., 2013. A simple equilibrium model for predicting shoreline change. *Coast. Eng.* 73, 191–202.
- De Santiago, I., Morichon, D., Abadie, S., Castelle, B., Liria, P., Epelde, I., 2013. Video monitoring nearshore sandbar morphodynamics on a partially engineered embayed beach. *J. Coast. Res. (Sp. Issue)*, 458–463.
- DHI, 2014. Manuals for MIKE21 SW and LITPACK. Danish Hydraulics Institute.
- DHI, 2016. *Marine Climate Change Guidelines*. July 2016, Technical Report.
- Dobrynin, M., Murawski, J., Yang, S., 2012. Evolution of the global wind wave climate in CMIP5 experiments. *Geophys. Res. Lett.* 39, L18606. <https://doi.org/10.1029/2012GL052843>.
- Dobrynin, M., Murawski, J., Baher, J., Ilyina, T., 2015. Detection and attribution of climate change signal in ocean wind waves. *J. Clim.* 28, 1578–1591.
- Glejin, J., Sanil Kumar, V., Nair, T.M.B., 2013. Monsoon and cyclone induced wave climate over the nearshore waters off Puducherry, South western Bay of Bengal. *Ocean Eng.* 72, 277–286.
- Grabemann, I., Weisse, R., 2008. Climate change impact on extreme wave conditions in the North Sea: an ensemble study. *Ocean Dyn.* 58, 199–212.
- Haibin, Li, Sheffield, Justin, Wood, E.F., 2010. Bias correction of monthly precipitation and temperature fields from Intergovernmental Panel on Climate Change AR4 models using equidistant quantile matching. *J. Geophys. Res.* 115 (D10).
- Hanson, J.L., Phillips, O.M., 1999. Wind sea growth and dissipation in the open ocean. *J. Phys. Oceanogr.* 29, 1633–1648.
- Hemer, M.A., Church, J.A., Hunter, J.R., 2007. Waves and climate change on the Australian Coast. *J. Coast. Res. SI* 50, 432–437.
- Hemer, M.A., Wang, X.L., Church, J.A., Swail, V.R., 2010. Coordinating global ocean wave climate projections. *Bull. Am. Meteorol. Soc.* 91 (4), 451–454.
- Hithin, N.K., Sanil Kumar, V., Shanas, P.R., 2015. Trends of wave height and period in the Central Arabian Sea from 1996 to 2012: a study based on satellite altimeter data. *Ocean Eng.* 108, 416–425.
- IPCC, 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom & New York, NY, USA, p. 1535.
- Kudale, M.D., 2010. Impact of port development on the coastline and the need for protection. *Indian J. Geo-Mar. Sci.* 39 (4), 597–604.
- Kulkarni, S., Deo, M.C., Ghosh, S., 2016. Evaluation of wind extremes and wind potential under changing climate for Indian offshore using ensemble of 10 GCMs. *Ocean Coast. Manag.* 121:141–152. <https://doi.org/10.1016/j.ocecoaman.2015.12.008>.
- Kundu, S., Mondal, A., Khare, D., Mishra, P., Shukla, R., 2014. Shifting shoreline of Sagar Island Delta, India. *J. Maps* 10 (4), 612–619.
- Liu, Y., Li, M., Zhou, M., Yang, K., Mao, L., 2013. Quantitative analysis of the waterline method for topographical mapping of tidal flats: a case study in the Dongsha sandbank, China. *Remote Sens.* 5:6138–6158. <https://doi.org/10.3390/rs5116138>.
- Mancini, F., Dubbini, M., Gattelli, M., Stecchi, F., Fabbri, S., Gabbianelli, G., 2013. Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: the structure from motion approach on coastal environments. *Remote Sens.* 5, 6880–6898.
- Mani Murali, R., Shrivastava, D., Vethamony, V., 2001. Monitoring shoreline environment of Paradip, East coast of India using remote sensing. *Curr. Sci.* 97 (1), 79–84.
- Mani Murali, R., Dhiman, R., Choudhary, R., Jaya Kumar, S., Ilangoan, D., Vethamony, P., 2015. Decadal shoreline assessment using remote sensing along the central Odisha coast, India. *Environ. Earth Sci.* 74 (10), 7201–7213.
- Mason, D., Davenport, I., Robinson, G.J., Flather, R.A., McCartney, B.S., 1995. Construction of an inter-tidal digital elevation model by the “water-line” method. *Geophys. Res. Lett.* 22, 3187–3190.
- Mason, D.C., Amin, M., Davenport, I.J., Flather, R.A., Robinson, G.J., Smith, J.A., 1999. Measurement of recent intertidal sediment transport in Morecambe Bay using the water-line method. *Estuar. Coast. Shelf Sci.* 49, 427–456.
- Mohanty, P.K., Patra, S.K., Bramha, S., Seth, B., Pradhan, U., Behera, B., Mishra, P., Panda, U.S., 2012. Impact of groins on beach morphology: a case study near Gopalpur Port, East Coast of India. *J. Coast. Res.* 28 (1), 132–142.
- Mori, N., Shimura, T., Yasuda, T., Mase, H., 2013. Multi-model climate projections of ocean surface variables under different climate scenarios—future change of waves, sea level and wind. *Ocean Eng.* 71 (1), 122–129.
- Naren, A., Maity, R., 2016. Hydroclimatic modelling of local sea level rise and its projection in future. *Theor. Appl. Climatol.* <https://doi.org/10.1007/s00704-016-1897-4>.
- Nicholls, R.J., Larson, M., Capobianco, M., Bwekemei, W.A., 1998. Depth of closure: improving understanding and prediction. *Coast. Eng.* 28:888–2901. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.935.2176&rep=rep1&type=pdf>.
- Omid, M.H., Karbasi, M., Farhoudi, J., 2010. Effects of bed-load movement on flow resistance over bed forms. *Sadhana* 35 (6), 681–691.
- Paine, J.G., Morton, R.A., 1989. *Shoreline and vegetation-line movement, Texas Gulf Coast, 1974–1982, Galveston Bay Bibliography*, Texas Digital Library. <https://repositories.tdl.org/tamug-ir/handle/1969.3/19375>.
- Panigrahi, J.K., Sathish, K.V., Tripathy, J.K., 2010. Littoral drift by alongshore flow at Visakhapatnam – East Coast of India. *J. Hydro Environ. Res.* 4 (4), 317–327.
- Parker, K., Hill, D.F., 2017. Evaluation of bias correction methods for wave modelling output. *Ocean Model* 110, 52–65.
- Patra, A., Bhaskaran, P.K., 2016. Trends in wind-wave climate over the head Bay of Bengal region. *International. J. Climatol.* 36, 4222–4240.
- Rajashree, B.R., Deo, M.C., Nair, Sheela, 2016. Effect of climate change on shoreline shifts at a straight and continuous coast. *Estuar. Coast. Shelf Sci.* 183, 221–234.
- Reeve, D., Chadwick, A., Fleming, C., 2015. *Coastal Engineering: Processes, Theory and Design Practice*. CRC Press, Florida, pp. 205–262.
- Sanil Kumar, V., Pathak, K.C., Pednekar, P., Raju, N.S.N., Gowthaman, R., 2006. Coastal processes along the Indian coastline. *Curr. Sci.* 91 (4), 530–536.
- Sarma, K.G.S., 2015. Siltation and coastal erosion at shoreline harbours. 8th International Conference on Asian and Pacific Coasts. *Proceedia Eng.* 116, 12–19.
- Semedo, A., Suselj, K., Rutgersson, A., Sterl, A., 2011. A global view on the wind sea and swell climate and variability from ERA-40. *J. Clim.* 24, 1461–1479.
- Shanas, P.R., Sanil Kumar, V., 2014. Temporal variations in the wind and wave climate at a location in the eastern Arabian Sea based on ERA-interim reanalysis data. *Nat. Hazards Earth Syst. Sci.* 14, 1371–1381.

- Sobral, F., Pereira, P., Cavalcanti, P., Guedes, R., Calliari, L., 2013. Intertidal bathymetry estimation using video images on a dissipative beach. *J. Coast. Res.* (65), 1439–1444.
- Sundar, V., Ananth, P.N., Sarma, K.G.S., 1987. Distribution of Longshore Currents and Sediment Transport Rates in the Surf Zone off Paradip, India. *Proceedings: OCEANS '87, Halifax, Nova Scotia, Canada, September 28–October 1, 1987* pp. 970–974.
- Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* 93 (4), 485–498.
- Trenhaile, A.S., 2010. Modelling cohesive clay coast evolution and response to climate change. *Mar. Geol.* 277 (1–4), 11–20.
- Varadarajulu, R., Hari Krishna, M., 1979. Wave characteristics off paradip port. *Indian J. Mar. Sci.* 8, 68–72.
- Watanabe, Y., Mori, N., 2008. Infrared measurements of surface renewal and subsurface vortices in nearshore breaking waves. *J. Geophys. Res.* 113, C07015.
- Wilson, K., 1989. Friction of wave induced sheet flow. *Coastal Eng.* 12, 371–379.
- Wu, L., Qin, Jie, Teng, Wu., Li, Xing, 2017. Trends in global ocean surface wave characteristics as represented in the ERA-Interim wave reanalysis for 1979–2010. *J. Mar. Sci. Technol.*:1–8 <https://doi.org/10.1007/s00773-017-0450-1>.
- Yates, M.L., Guza, R.T., O'Reilly, W.C., Hansen, J.E., Barnard, P.L., 2011. Equilibrium shoreline response of a high wave energy beach. *J. Geophys. Res.* 116, C04014. <https://doi.org/10.1029/2010JC006681>.
- Young, I.R., Ziegei, S., Babanin, A.V., 2011. Global trends in wind speed and wave height. *Science* 332 (6028), 451–455.
- Zacharioudaki, A., Reeve, D.E., 2011. Shoreline evolution under climate change wave scenarios. *Clim. Chang.* 108 (1), 73–105.
- Zhang, K., Douglas, B., Leatherman, S., 2002. Do storms cause long-term beach erosion along the U.S. East Barrier Coast? *J. Geol.* 110 (4), 493–502 (the University of Chicago Press).
- Zhao, Dongliang, Toba, Yoshiaki, 2001. Dependence of whitecap coverage on wind and wind-wave properties. *J. Oceanogr.* 57, 603–616.